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Charge sharing on monolithic CdZnTe gamma-ray detectors: A simulation study

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Abstract

Monolithic CdZnTe gamma-ray detectors are used to build gamma cameras for nuclear medicine imaging but their energy resolution is currently limited by charge sharing between adjacent anodes. For this work, charge sharing is simulated using Ulysse, a numerical model that takes into account the physical processes of charge creation by ionizing radiation and charge transport within the semiconductor detector. The charge carrier cloud size, following the gamma-ray photon interaction, is computed by the Monte Carlo method. Electron cloud diffusion and charge induction on the electrodes are computed by the finite element method. This study shows that the electron diffusion strongly influences the final electron cloud diameter.

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Keywords: Gamma-ray detector; CdZnTe; Numerical simulation; Charge sharing

1. Introduction

Monolithic CdZnTe detectors are promising for medical applications and small animal imaging, thanks to their good energy resolution that allows both multi-isotope diagnostics and scatter rejection. However, the full potential of CdZnTe detectors has not yet been realized because of the loss of detected events improperly rejected from the full-energy peak due to the low-energy tail of the spectrum [1]. The tailing results mainly from the dependence of the induced signal on the interaction depth and from charge sharing between adjacent anodes. Depth of interaction corrections has been studied elsewhere [2]. Since understanding charge sharing becomes increasingly important as the anode size is reduced, we have carried out a simulation study of this effect. First, charge sharing is assessed by studying the interaction of gamma rays with matter. Next the effects of charge-carrier diffusion and charge induction are added. Finally, a qualitative comparison with experimental results is presented.

In this work, our attention is focused on typical CdZnTe gamma-ray pixelated detectors suitable for gamma cameras (5 mm thickness for 122 keV photons).

2. Ulysse

Recently, an accurate model for determining the three-dimensional distribution of charge pulses produced in a semiconductor detector has been developed [3,4]. It is divided into three parts. (1). A Monte Carlo code, based on PENELOPE [5], is used to follow gamma-ray photon histories in the semiconductor crystal and to simulate pulse height spectra. (2). The charge transport and charge induction efficiency are computed using an adjoint method [6], with the finite element method-based FEMLAB commercial package [7]. The adjoint method has the advantage of providing continuous mapping of the induced charge pulse at any time and for any interaction point, with a single transient finite element computation. (3). A signal-processing module models the readout electronic response, including noise and biparametric [2] signal processing methods.

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3. Gamma-ray interaction with the crystal

In this section, charge sharing is assessed by only studying the interaction of gamma-rays with matter. The electron cloud size following the photon interaction is computed by the Monte Carlo method for a 5 mm thick CdZnTe detector. At 122 keV, 82% of interactions are photoelectric interactions, 11% are Compton scattered and 7% are Rayleigh scattered. After photoelectric absorption, the deexcitation can be followed by the ejection of Auger electrons (25% of events in CdZnTe) or X-ray fluorescence (27–31 keV for tellurium, 23–26 keV for cadmium and 8–10 keV for zinc). A cadmium atom can absorb a tellurium X-ray fluorescence photon by photoelectric absorption and a second fluorescence can follow the first one. The mean distance covered by fluorescence photons is presented in Table 1.

The mean distance covered by X-ray fluorescence photons is 90 μm but, when the population of Auger electron ejection events is included, the mean distance covered by the entire population is 67 μm at 122 keV in CdZnTe. The mean distance covered by the initial photoelectron is 10 μm. Fig. 1 shows the electron cloud diameter distribution computed by Monte Carlo method. We see that 50% of the electron clouds have a diameter inferior to 36 μm, 80% inferior to 120 μm, and 90% inferior to 190 μm.

Table 1
Monte Carlo study of the distance from the initial interaction location to the last fluorescence photon interaction (distance projected on the *xy* plane)

Fluorescence number	Ratio (%)	Mean distance (μm)
0 (Auger)	25	7
1	45	75
2	25	111
⩾3	5	118
Fluorescence only	75	90
All events	100	67

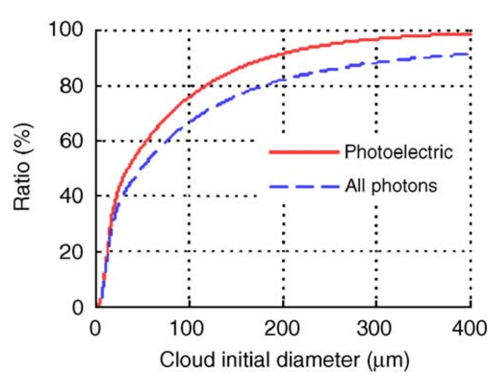

Fig. 1. Ratio of events whose size is inferior to the distance in abscissa (5 mm thick CdZnTe detector at 122 keV).

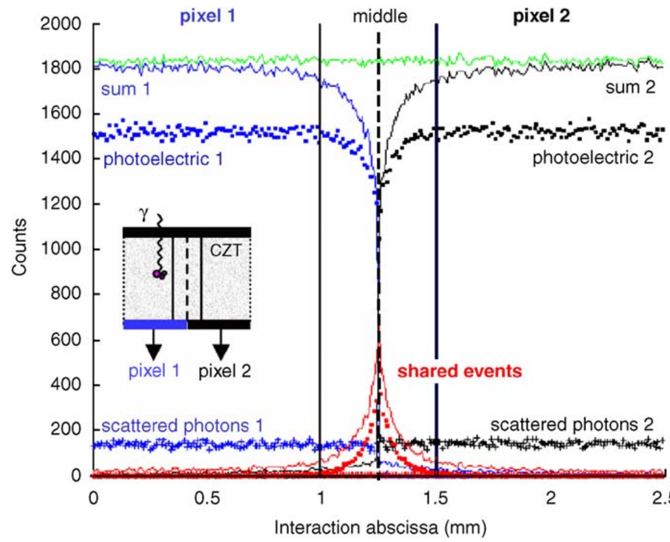

Fig. 2. Number of events counted by one anode and an adjacent one and the number of shared events counted both as a function of the first interaction location. Computation was performed for photoelectric events (square points), Compton and Rayleigh scattering (crosses) and for all events (solid line). 5 mm thick CdZnTe detector at 122 keV.Distance between the reference vertical black lines is 500 μm. There are no gaps between anodes.

In order to model charge sharing between adjacent anodes, the energy deposited under each anode is compared to an energy threshold (15 keV) as a function of the first photon-interaction location (Fig. 2). Depending on the electron cloud dispersion above the two pixels, the event is detected by a single anode or by two adjacent anodes.

Charge sharing is significant at least to a distance of 80 μm, the full-width at half-maximum (FWHM) and registers as far as 250 μm due to Compton scattering. Over the full area of the detector, 5.3% of events are shared at 122 keV for a 2.5 mm pitch detector. The ratio of shared events increases to 13% and 25% of total events for 1 mm and 500 μm pitch detectors, respectively.

4. Model including charge induction and electron diffusion

In this section, interaction of gamma-rays with matter is coupled with a model of charge induction on the anode and electron cloud diffusion. The detector response is modeled with the adjoint method [3,4] to obtain a map of the charge induction efficiency (CIE) (Fig. 3). The CIE map is the normalized signal induced by an interaction at any point in the detector. The CIE map contains all the information necessary to complete the simulation of the detector.

Assuming a point-like interaction, the deposited electron cloud is enlarged by diffusion, leading to charge sharing near the middle of the interpixel space (Fig. 4). In this example, the threshold value is 12% of the deposited charge (equivalent to a 15 keV threshold for 122 keV photon). If the normalized CIE associated with pixel 1 is